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Optimization of Firefighting capacity using Network Analysis: Case Study of Kathmandu Valley

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Abstract
Despite the fact that fire is the most common and economically costly disaster, fire response and preparedness appear to be significantly limited, particularly in the Kathmandu valley. Only four operational fire stations, excluding army and aviation authorities, are presently responding to fire disasters in the valley. Due to this, it is impossible for these firefighters and fire brigades to arrive at the accident scene on time. This research studies about the current response time capacity of the fire station inside Kathmandu valley using service area of network analysis in an open-source program, QGIS. Furthermore, the minimum optimal number of locations for fire stations required is calculated using open-source model, Allagash method using python programming. The result of this research shows that the valley is severely lacking in maintaining the response time of 10 minute due to lack of number of fire station. At least 56 number of fire station or fire truck at several locations is required to serve population optimally inside Kathmandu Valley.

Keywords
Firefighting, Kathmandu Valley, Optimization, Response time, Network Analysis, Fire, Brigade, Station

1. Introduction

Nepal is considered to have a large amount of fire disasters every year for a very long period of time. Fire has been causing around 5 percent of severe disabilities to its victims in Nepal. This number is higher in highly dense areas with poorly developed urban settings with a large number of plastic disposals which assists the fire spreading.[1] Even while fire kills fewer people than other major disasters such as earthquakes, floods, and landslides, the average loss of property due to fire is considerable. The Kathmandu Valley is becoming more prone to fire as a result of unplanned urbanization and population growth. Systematic studies, such as fire potential mapping and risk assessment, are required to control fire concerns.[2]

Despite the fact that fire is the most common and economically costly disaster, fire response and preparedness appear to be significantly limited, particularly in the Kathmandu valley. Only four operational fire stations, excluding army and aviation authorities, are presently responding to fire disasters in the valley. The fire stations, on the other hand, merely use standard station management practices, proper firefighting equipment, and operational issues common among frontline urban firefighters.[1]

If the fire fighters cannot reach the destination within a specific time period, there is bound to be a large amount of property loss. Therefore, there is a very essential need of analyzing if the current number of fire stations in the city is of the required number or not. The distance from the fire station to the destination is one of the influencing factors for the response time. There are other factors as well which affect the response time, such as population density, accessibility, land zones, traffic condition, time, socio-culture and administration and operation.[3] The total response time includes call processing time, turnout time, and travel time[4]:

- Call processing time – the time passed between when the call was received at the Concerned department and when the first unit was dispatched.
- Turnout time – the time passed between when a unit is dispatched and when that unit's status changes to responding.
- Travel time – the amount of time that elapses

between when a unit begins to respond and when it arrives on the site

Fire is such an entity that can increase exponentially if left for a longer period. A fire is sometimes characterized as "doubling in size every minute." On a graph, the extent of such a fire would result in a curving line like the one illustrated in Figure 1.[5]

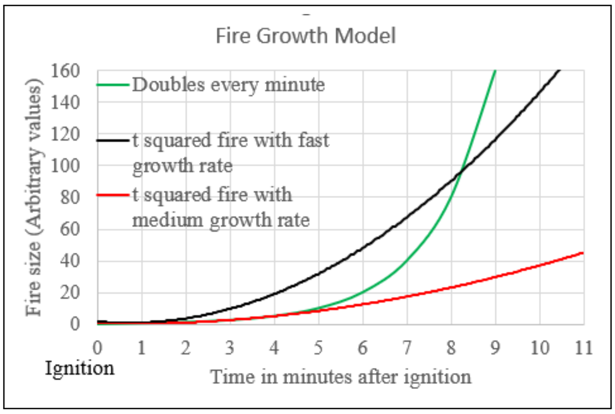

Figure 1: Graphical representations of fire growth (Source: The Fire Brigades Union, 2010)

The crucial thing to notice in the Figure is that the rate at which any fire grows in magnitude grows with time. For example, the fire with fast growth rate increases in size by roughly 12 units between minutes 3 and 4, then by almost 40 units between minutes 9 and 10. This shows that, initially fire may not be strong enough to destroy property or cause human casualties, but after over 10 minutes of fire, every minute can cause more harm and is more hazardous. Therefore, response time before the increase in fire is essential.

1.1 Research Purpose

There are many cases of urban fire each year inside Kathmandu valley. During the last one year (from November 2020 to 2021) there were 56 recorded cases of fire inside Kathmandu metropolitan city only [6]. This data excludes other districts inside Kathmandu valley and also other municipalities inside Kathmandu district. From this, we can see that there is an essential need to see if the current fire stations assigned are in adequate quantity. With this, following research questions needs to be studied to research the area properly.

- Is the present response time of fire brigade sufficient to serve the firefighting demand of the valley?
- How many additional fire stations can serve the valley optimally with current road network?

This research paper studies about the current capacity of the fire station inside Kathmandu valley using Network Analysis in GIS (Geographic Information System) software and Allagash model using Python programming. The objectives of this research is:

- To analyze response time of fire brigade departments using GIS to reach different destinations within Kathmandu Valley.
- To optimize the response time by analyzing the total number of required stations.

2. Fire During Emergency

When an emergency is reported, the most important factor is time. As time passes, the fire will spread, reducing the chances of successfully removing the residents. The amount of time between the commencement of the fire and the start of the fire suppression has a clear correlation with the fire damages. Most residential fires go through the same stages, regardless of how quickly they spread. When the fire has completely consumed the room, this is one of those stages. The Flashover is the name for this level. There are numerous elements that influence when flashover occurs. The type and amount of fuel, the location of the fuel in the room, size of the room, ignition type, weather conditions, and other factors are among them.[3]

Prajapati in his thesis study "An Evaluation of Fire Safety Measures in High Rise Residential Buildings: A Case of Kathmandu Valley, Nepal" has stated that according to the Metropolitan Police Office, short-circuits cause the majority of fires in Kathmandu Valley. Other causes of fire incidents include kitchen fires, improper handling of matches and lighters, electrical shorts in vehicles, improper handling of an oil-fed lamp in a prayer room, and so on. The primary causes of fire outbreak are short-circuiting, overheating of electronic devices, fluctuating voltage and electric spark after a sudden continuation of power supply just after load-shedding, poor handling of flammable lamps, and cooking gas leakage. Metropolitan Police Office or Juddha Barun Yantra receives one call per day to respond to fire incidents on average.[7]

2.1 Fire Brigade Present scenario

Juddha Samsher, the then-Rana Prime Minister, established this fire station in 1938, 4 years after the large earthquake in 1934. The fire engines came from England. The city had a population of only 60,000 people at the time, and most of the houses were concentrated near the Durbar Square, which was once a royal palace. Houses were only about five floors tall at the time. Since then, neither technology nor the firefighting system has advanced significantly[8]. It can take up to 5 hours to put out a fire. A fire in a straw store near the Pashupati temple once lasted 4 to 5 days. It took 7 hours to put out a fire in a house near the Naryanhiti Museum, which was once the Royal Palace. The property loss in that particular instance was approximated to be above NRs. 5 million. The fire station also serves neighboring cities such as Lalitpur, Bhaktapur, and Kirtipur, as well as the adjacent Villages. The Kathmandu Fire Brigade also serves municipalities and placess up to 30 kilometers away, including Kirtipur Municipality, Panauti, Lubhu, and Sankhu. In the past, there have been approximately 350 cases per year, including search and rescue when people drown in a well.[7]

Various cities have varying number of fire stations. Some of the major cities are listed in Table 1:

Table 1: No. of fire station in various cities worldwide

City	Fire station count	City area (Km^2)
Kathmandu Valley	4	933.4
Delhi	64	1483
New York	218	783.8
London	102	1572
Toronto	83	630.2
Vancover	20	115
Tokyo	81	627.6
Paris	81	105.4
Los Angeles	106	1299

From the table 1 as well, we can see that number of fire station in Kathmandu valley is severely lacking. Most of the cities worldwide has focused their resources on urban fire by deploying fire station at various location of the city. However, Kathmandu valley which also has the capital city Kathmandu has very less number of fire station managing the whole valley.

Questionnaire Survey with Chief of fire station was conducted in fire brigade head office located in Newroad. Fire truck faces difficulties due to traffic congestion, potholes as well as wires hanging around in the city area. These factors severely increase the response time. Firefighting motorcycles are also being used regularly. However, they can only be used in small fire incidents such as fire on electric poles or other such small fire where smoke extinguishers can be used. During peak hours of Kathmandu valley, speed of fire truck ranges from 20 Kmph to 35 Kmph. Most of the road user are educated and provide access way for emergencies vehicles, hence the speed can be maintained to 20-35 Kmph in peak hours. However, speed in very narrow road is severely less. Some pedestrian only type of road cannot even be accessed by fire truck.

Furthermore, it has also been researched that average speed of motorcycle in Kathmandu valley is 29.79 Kmph with standard deviation of 6.72 Kmph in one way 3.6m roads, two way undivided 3.25m roads have speed of 24.35 Kmph with standard deviation of 6.63 Kmph and two-way undivided road with width 2.95m has 20.25 Kmph with standard deviation of 5.25 Kmph [9]. From the survey questionnaire with fire department as well as study of past research studies, it can be found that speed of motorcycle in Kathmandu valley is similar to the speed of emergency vehicles.

3. Methodology

This research study falls under post positivist paradigm. The research is quantitative in nature as it looks at time and speed factor of fire brigade response time. Furthermore, the research is based on simulation that is to be carried out using existing road data. Therefore, it uses natural science which is to be researched using scientific technology. There are several aspects to consider when determining how many people a fire station can serve. The phrase "network analysis" in GIS refers to operations that look at traveling time, service areas, and other GIS issues that need knowledge of and comprehension of a road network. GIS network analysis is a broad topic that involves numerous ideas and procedures from the domains of computer science and mathematics. Dijkstra's algorithm, developed by computer scientist Edsger W. Dijkstra in 1956, is particularly significant in this context because it is still employed in both computer science and GIS generations later. [10]. QGIS (Quantum GIS) uses Dijkstra's algorithm to analyze the network problems. Service area function in QGIS also uses the same algorithm [11]. The goal of service area function is to generate a vector containing all of the network layer components that can be reached within a specified time or distance from a point on the map. The service area solver can generate lines[12]. Service area can provide area coverage by current fire stations in the valley.

Location covering model or optimization model is commonly used to determine the best spatial configuration of a collection of facilities that provide some level of service to demand units. It is frequently necessary to ”cover” demand within a certain time or distance [13]. Location optimization can be done using various models such as ArcGIS, PySpatialOpt, Maxcovr and FLP (Facility Layout Problems) Solver. However, the conclusion made by research by Chen et al showed that in terms of way to solve optimality, scalability, and distance types, PySpatialOpt and Maxcovr surpass FLP Solver and ArcGIS. However, While the documentation for PySpatialOpt and FLP Solver is extensive and clear, documentation for the MCLP (Maximum Covering Location Problem) in Maxcovr, and documentation of ArcGIS is limited. [14]. By observing the conclusion made by the research, this research uses Allagash model, which is an updated version of PySpatialOpt. The model solves with the help of mathematical solver, GLPK (GNU Linear Programming Kit) and runs alongside open-source project Geopanda which is a geospatial operator working with the help of Python Programming. The most recent version of Allagash supports the Location Set Covering Problem (LSCP) and Maximum Covering Location Problem (MCLP) models only [13]. This study uses the LSCP for the optimization of fire stations.

4. Data Analysis and Results

The spatial data required for analysis has been obtained from various sources such as internet open sources open street maps, geofabrik.de, data.humdata.org, opendatanepal.com. Coordinates are obtained from google map and verifying by manually visiting. Speed is obtained from manual driving through peak hour as well as past research paper data and validating it with survey questionnaire taken with fire department.

4.1 Service Area

Service area can be obtained by calculating the total time required to travel through the road network to or from the provided facility. For Fire station, the fire trucks require to serve the population, therefore, the service area is taken for travel distance from fire station to various locations around the station. For this, the required data are location of stations, road network and its parameters like one way street data, road speed to obtain the time of travel in each road segments.

Road network for Kathmandu valley was taken from open street map for the study. The map obtained from the source has various road categories which has been compiled and grouped in this research as Track grade 2, Ring Road, primary roads, secondary roads, service road, arterial road, residential streets, living street and pedestrian street. Further, for research study purposes, speed of each road segment has been obtained based on manual bike survey during peak hours as well as study research by Hemant Tiwari. The speed of roads in major roads of Kathmandu valley ranges from 22 Kmph to 31 kmph [15].The speed taken has been validated with speed in field as experienced by fire truck driver with the help of open-end questionnaire survey with fire department, in which it was found that fire department experiences speed of fire truck ranges from 20Kmph to 35 Kmph during peak hours in Kathmandu valley. With this study, following table 2 data has been put into effect:

Table 2: Implemented speed for analysis

Categories	Speed Implemented (Kmph)
Track grade 2	35
Ring Road	30
Primary Road	27
Secondary Road	25
Service Road	40
Arterial Road	25
Residential Street	20
Living Streets	12
Pedestrian streets	10

Service area is analyzed with input of fire station location and time taken by fire truck to cover each road segment. In the current scenario, the four fire stations serve the entire valley as well as some parts beyond the valley area as well. However, interview with chief of fire department revealed that further 2 minute is taken in call processing time and turnout time. Service area study for fire stations is taken for response time of up to 10 minute and beyond that time is considered a critical zone [16]. Therefore, in the service area taken the calculation is done for 8 minutes as it corresponds to 10 minutes of response time. Figure 2 shows the safe response area of current fire stations and critical areas which cannot be reached even after 10 minute travel time. It is also found that the current fire station serves only 81.01Km^2 of total valley area of 933.4 Km^2.

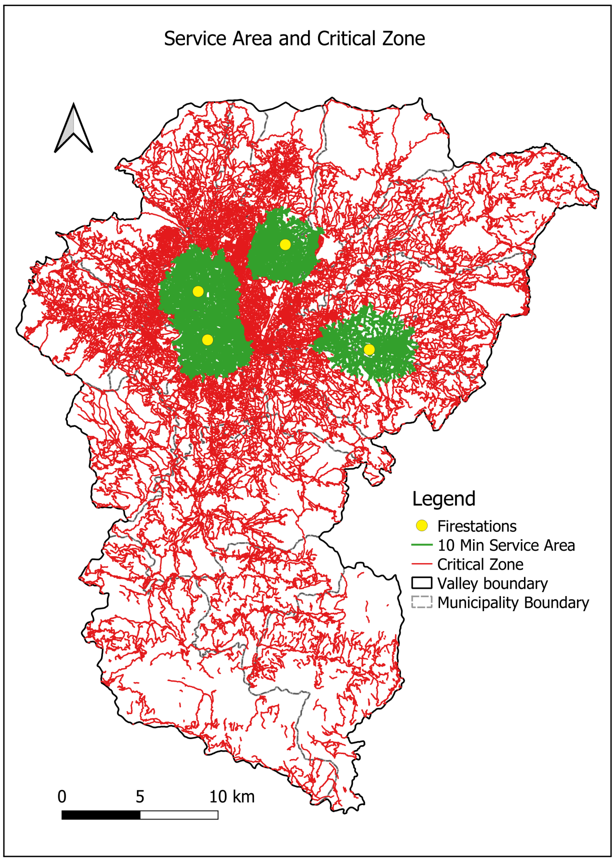

Figure 2: Safe Response zone and Critical Zone

4.2 Location Optimization

This research study utilizes open-source model, Allagash model which is an upgraded version of PySpatialOpt and works along with Python programming and a mathematical solver GLPK. The model works with Geopanda to take spatial vector data [13]. To work with the model, several numbers of service area polygons are required which can be obtained from other GIS software. It also requires the input of demand points for allocating the required numbers of fire stations in required locations. For location optimization, the data required are several numbers of candidate sites for proposed station and demand points. For this research, 2000 numbers of random candidate site are taken throughout the valley so that maximum locations can be utilized to calculate the optimal number of locations required in the valley.

QGIS provides service area in line vector format. Therefore, to work with Allagash model, the vector data has to be changed into polygon to obtain service area polygon. The obtained line vector has been converted to polygon vector with the help of convex hull tool, which outlines the outer area of points or line triangulation.

Demand points are locations that requires more attention of fire station and it requires quick response to the site. Therefore, the demand points in this research are taken as occupational buildings points, cultural sites points and fuel pump station points.The Figure 3 shows the service area polygons and demand points taken for the calculation of location optimization.

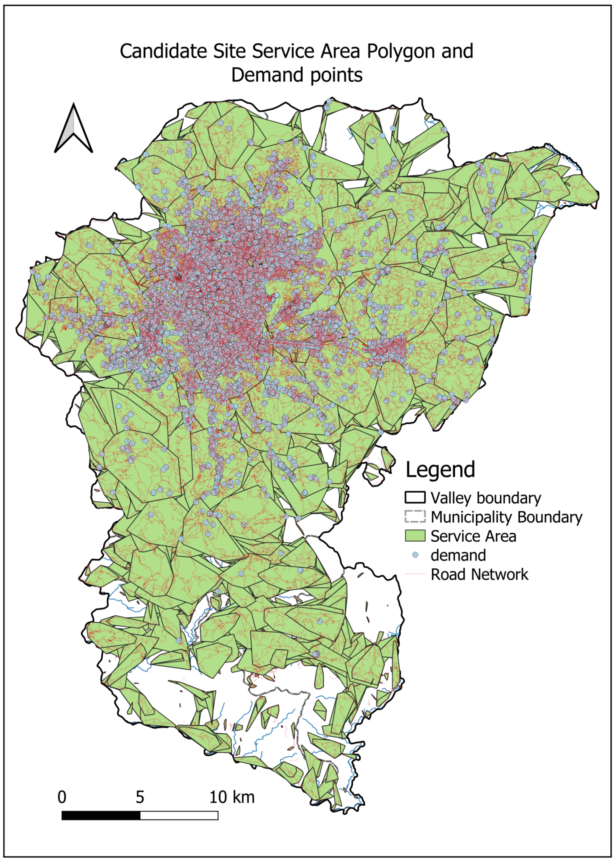

Figure 3: Service Area Polygons and Demand Points

With Location optimization using Allagash, it was obtained that, Kathmandu valley required minimum of 56 numbers of fire stations or stand by locations. The analysis was done for maximum response time of 10 minutes. This means at least 56 number of stations is required to serve optimally to all the population of the valley within 10 minutes of response time. Figure 4 shows locations allocated based on demand points using networks analysis.

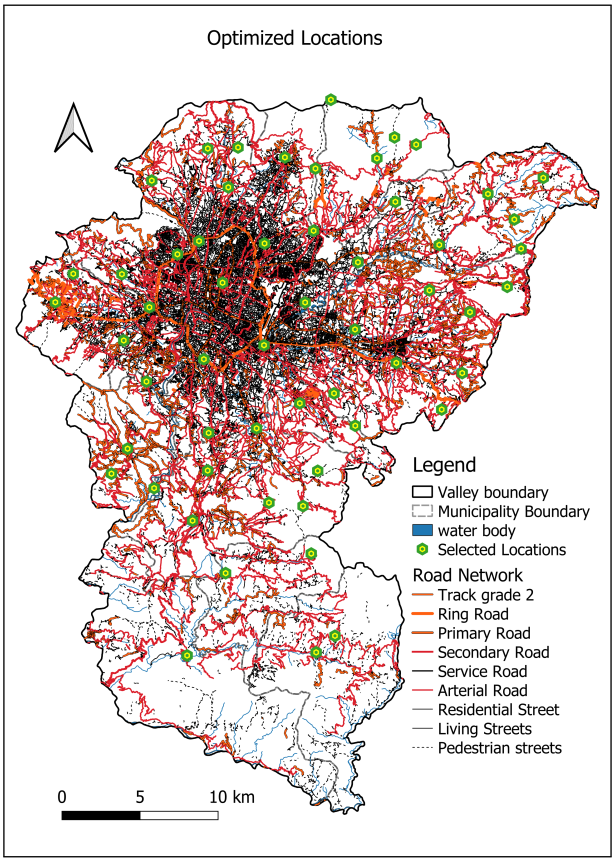

Figure 4: Optimal number of Fire station for the Valley

It can be observed that the allocated fire stations are more clustered toward Ring road areas. This is due to reason that the main city area has large amount of population demand points while the areas farther from main city has lesser roads as well as demand points.

The Table 3 shows the fire station count in each municipality as optimized by Allagash model. The station counts in Table 3 is varying in different municipality. This is due to various reasons like size of municipality as well as demand due to number of settlements and other demand criteria. Some outskirts of Kathmandu valley have hilly area where road does not connect directly with each other and has to move by going around the road. This creates more response time. Due to this, those regions require more stations. In some municipality, although its area is large, due to having low population and demand, small number of fire station can also serve the population with ease.

Table 3: No. of fire station located municipality wise

Municipality	Station Located	Municipality Area (Km^2)
Bagmati	1	111
Bhaktapur	0	7
Budhanilakantha	3	35
Chandragiri	2	44
Changunarayan	4	63
Dakshinkali	4	43
Godawari	7	96
Gokarneshwor	5	58
Kageshwori Manahora	3	27
Kathmandu	3	49
Kirtipur	1	15
Konjyosom	2	44
Lalitpur	1	36
Madhyapur Thimi	0	11
Mahalaxmi	1	27
Mahankal	2	82
Nagarjun	3	30
Shankharapur	5	60
Suryabinayak	5	42
Tarakeshwor	2	35
Tokha	2	17

5. Conclusion

Firstly, for the research question that, if the number of fire station in present context sufficient for the Kathmandu valley, it is noted that most parts of Kathmandu valley are in a critical zone as it lies beyond 10 minutes of response zone from the fire stations. The service area analysis of currently existing four stations shown in Figure 2 Safe Response zone and Critical Zone shows that the current fire stations serve only small portion of the valley and leaves most part of the valley in vulnerable situation. The service area of current fire station covers only 81.01 Km2 (covers only 8.68%) out of total valley area of 933.4 Km2. The effective response distance of current fire stations seems to be very low as it does not cover all the parts of Kathmandu valley which can leave the valley into hazardous situations if left alone. Moreover, the current fire stations in the city have to not only cover parts of city areas, but also the whole Kathmandu valley and sometimes beyond that area. There seems to be a significant need for improvement in the number of fire stations that need to be deployed in case of massive fire disasters.

Furthermore, if there is more than one fire disaster happening at the same time, the current fire stations cannot cover all the areas and has to depend upon the local population to take fire eliminating measures until the assistance from fire station can arrive at site.

Secondly, for the research question about number of fire stations that are required to optimally serve the total demand of Kathmandu valley, from this research, it is found that at least 56 number of fire stations are required for that fire brigade to function properly inside the valley. Fire station is required to be at least at 10-minute of response time zone. It should not exceed 10-minute time of travel else there will be chances of flash fire which will be even more difficult to take out and the fire extinguishing works might extend hours to subdue the fire. Due to this, the least amount of fire station location needed is calculated using 10-minute response time using the model. The result obtained in Figure 4 Optimal number of Fire station for the Valley was that, the valley required at least 56 numbers of fire stations throughout the valley.

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